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EXPERIMENTAL RESEARCH ON THE PENETRATION BEHAVIOR OF COMPACT TOROID FUELING ON EAST

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Abstract

Compact Torus (CT) technology has developed rapidly in recent years, CT is a high-density, self-organized plasma configuration characterized by its robust magnetic topology and high directional kinetic energy density. Due to these properties, CT exhibits exceptional capability to penetrate strong magnetic fields, making CT injection one of the most promising techniques for core fueling in future fusion reactors. A compact torus injection system (EAST-CTI) has been developed and successfully deployed for fueling experiments on the Experimental Advanced Superconducting Tokamak (EAST).Currently, the detection of injection depth during compact torus injection (CTI) core fueling processes primarily relies on electron cyclotron emission imaging (ECE) and reflectometer (REFL) diagnostics. While ECE and REFL offer advantages in plasma diagnostics, they suffer from limitations such as reduced accuracy due to high-temperature experimental environments, localized measurement constraints, and the complexity of data interpretation requiring specialized expertise.This investigation demonstrates an innovative methodology employing high-speed Charge Coupled Device(CCD) imaging systems to systematically document fuel injection dynamics in CTI core configurations, combined with image processing techniques and deep learning models to analyze the CCD images and quantify the dynamic variation of injection depth. Experimental results indicate that the deep learning-based image segmentation method exhibits excellent performance in the determination of injection depth during the compact torus core fueling process. It demonstrates a certain degree of self-consistency with the diagnostic results of ECE and REFL, validating the feasibility of the algorithm. Moreover, image processing technology possesses advantages in injection depth diagnosis, such as a comprehensive field of view, high temporal resolution, and intuitive data interpretation. The development of this algorithm is of great significance for the efficient and accurate determination of injection depth during compact torus core fueling. In the future, the recognition efficiency and accuracy of the algorithm can be further enhanced by expanding the dataset.

1. INTRODUCTION

The commonly used fueling methods in tokamak devices mainly include conventional gas puffing[1], supersonic molecular beam injection(SMBI)[2], neutral beam injection(NBI)[3], and pellet injection(PI)[4]. Among them, neutral beam injection and pellet injection have become the most widely applied fueling methods in large-scale fusion devices nowadays. However, the neutral beam injection suffers from low and insufficient fueling efficiency due to the small particle flux it provides. For pellet injection, issues such as ablation and fuel deposition lead to premature ionization of fuel, and the pellet speed is difficult to meet the requirements. Thus, both methods are hard to be applied to the core fueling of future large-scale fusion reactors.In recent years, the compact torus(CT)[5] technology has developed rapidly. A compact torus(CT) is a high-density self-organized plasma blob. Owing to its robust magnetic structure and high directional kinetic energy density, it can penetrate strong magnetic fields. Therefore, compact torus injection(CTI) is regarded as one of the most promising technologies for realizing core fueling in future fusion reactors. At present, a compact torus injection system(EAST-CTI)[6] has been successfully developed on the fully superconducting tokamak EAST[7]. Conducting injection experiments in the EAST fusion device is of great research significance. This paper focuses on the research of the method for measuring the variation of injection depth during the core fueling process of the compact torus injection system.

Currently, the detection of injection depth during the core fueling process of the compact torus injection (CTI) system mainly relies on electron cyclotron emission imaging (ECE)[8] and reflectometer (REFL)[9] diagnostics. While ECE and REFL possess certain advantages in plasma diagnostics, they also have drawbacks,

such as detection accuracy being affected by experimental environments (e.g., high temperature), the locality of detection results, and the complexity and professionalism required for interpreting experimental data.This paper employs a high-speed CCD camera[10] to capture images of the core fueling process of the CTI system, and analyzes the CCD images via image processing technology to obtain the variation of injection depth. To investigate the variation of injection depth during the core fueling process of the CTI system, this paper adopts, for the first time, an image processing method combined with deep learning-based detection to determine the injection depth.

Image processing technology is widely applied in plasma diagnostics, mainly including plasma visualization, temperature and density measurement, and instability analysis. When combined with multi-channel imaging technology, it can simultaneously acquire multiple plasma properties (such as temperature and density), thereby improving the comprehensiveness and accuracy of diagnostics.With the rapid development of deep learning technology, an increasing number of studies have begun to apply it to plasma image processing. By training neural networks, automatic detection and classification of complex plasma phenomena[11], plasma boundary detection and reconstruction in tokamak devices, and extraction and identification of ELM filament structures can be achieved[12]. Among these, the U-Net neural network is a convolutional neural network (CNN) architecture widely used in image segmentation tasks.Proposed for the first time by Olaf Ronneberger et al. in 2015, the U-Net neural network is a special form of CNN, initially specifically designed for biomedical image segmentation tasks. Benefiting from its unique U-shaped network structure, which integrates the symmetric design of an encoder and a decoder, it enables efficient image segmentation.

In this paper, the images captured by a high-speed CCD camera are processed using image processing technology to make a preliminary determination of the injection depth. A core fueling dataset is created through manual annotation, and after training with the U-Net neural network architecture, accurate detection of the injection depth can be achieved.Comparing the diagnostic results of CCD camera images with those of ECE and REFL shows a high degree of self-consistency between them, which also verifies the feasibility of the method proposed in this paper. Moreover, image processing technology has advantages in injection depth diagnosis, such as a comprehensive field of view, high temporal resolution, and intuitive data interpretation. The development of this algorithm is of great significance for efficiently and accurately determining the injection depth during the compact torus core fueling process. In the future, the recognition efficiency and accuracy of the algorithm can be further improved by expanding the dataset.

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The structure of this paper is as follows: the second section briefly introduces the materials and methods; the third section presents the results; and the fourth section is dedicated to the conclusion and discussion.

2. MATERIALS AND METHODS

2.1. Datasets

CCD cameras play a crucial role in plasma diagnostics. Their high sensitivity, rapid response, and multi-dimensional data acquisition capabilities make them a key tool in plasma physics experiments. CCD cameras capture the transient evolution process of plasma through high-speed imaging. For instance, in tokamak devices, CCD are used to record the dynamic trajectories of neutral beam injection (NBI), molecular beam injection (MBI), and pellet injection. The position and depth at which the fuel penetrates the magnetic field are determined by analyzing the distribution of optical radiation. Therefore, during the fuel injection process in the core of a compact torus, we can use CCD to capture the bump structure (cold radiation ring) of the density distribution, then analyze its contraction-expansion behavior using algorithms such as edge enhancement, and quantify the injection depth of the fuel. The EAST is equipped with 16 ports dedicated to various diagnostic systems, heating systems, dosing

systems, and more. As shown in Figure 1, the Compact Torus Injection (CTI) system is installed at the H-port of the EAST device; the visible light camera system is arranged at the F-port, and the EAST-CTI device at the H-port falls within the horizontal field of view of this camera. Therefore, the visible light camera at the F-window can capture the complete core fuel injection process during CTI operation.

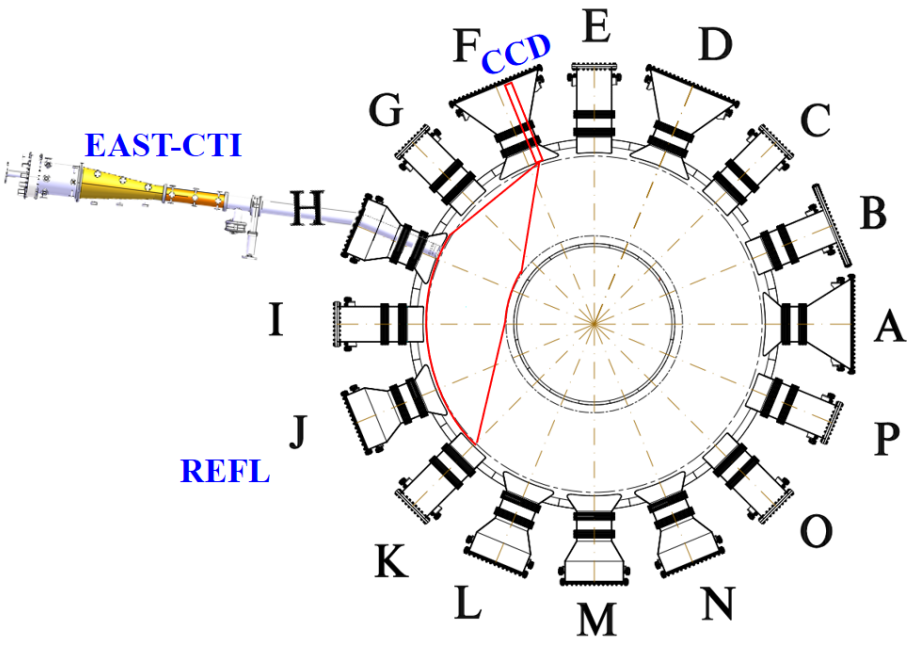

FIG. 1. Horizontal overhead view of the EAST device with 16 ports. The compact tours injection device is located at port H and the camera is located at port F. The red area is the horizontal field of view of the camera.

As shown in Figure 2,During the CTI core fuel injection process, visible light camera image analysis shows that within a millisecond scale time frame, the plasma density distribution exhibits an obvious protrusive structure. This protrusive structure demonstrates dynamic evolution characteristics of initiallycontracting inward and then expanding outward. The boundary of this transient structure is defined as the cold radiation ring, and the temporal variation of its spatial position directly reflects the dynamic changes in the injection depth of CTI core fuel injection. By extracting and enhancing the edge features of the cold radiation ring using CCD image recognition technology, the quantitative analysis of its position evolution provides key insights into the study of fuel penetration dynamics after CTI injection.

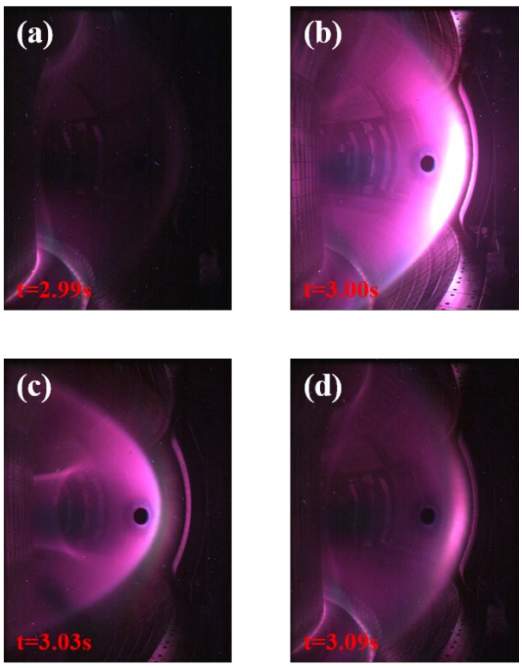

FIG. 2. Images of CTI fuel injection captured by CCD.

2.2. Methodology

To study the variation of injection depth during the compact torus core fuel injection process, this paper conducts experimental calibration on the visible light camera and completes the conversion between the 2D image coordinates and real-world coordinates. During the core fuel injection process of the compact torus injection system, the calibration of the visible light camera is a critical prerequisite for accurately determining the injection depth. Its core purpose is to establish an accurate mapping relationship between the image pixel coordinates and the real spatial coordinates of the EAST device, ensuring that the position measurement of the cold radiation ring has physical significance and quantitative accuracy. The camera calibration is illustrated in Figure 3.

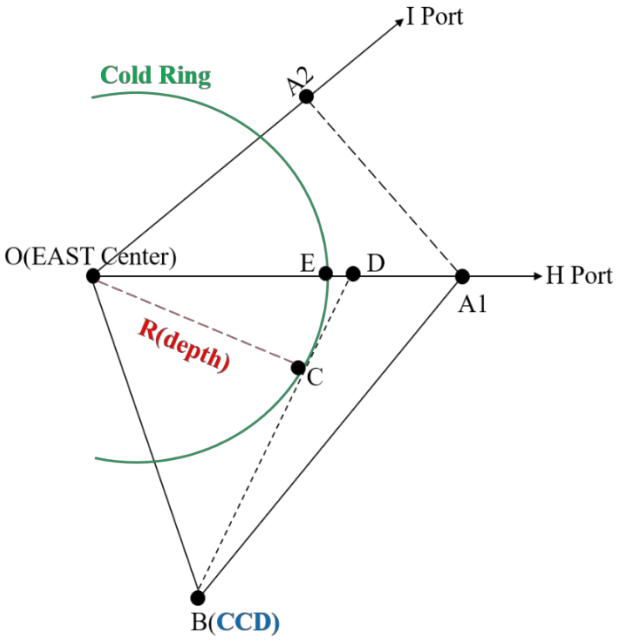

FIG. 3. Visible light camera calibration.

During the core fuel injection process of the compact torus injection (CTI) system, the cold radiation ring is a key transient feature reflecting the fuel injection depth, and its boundary position directly corresponds to the penetration depth of the fuel pellet. The use of deep learning models for cold radiation ring detection is a core method to address the limitations of traditional methods and achieve high-precision, high-robustness judgment of injection depth.

U-Net is a classic model for semantic segmentation tasks[13]. Its symmetric encoder-decoder structure and the design of skip connections perfectly match the detection requirement of precise edge localization for the cold radiation ring. The amount of image data from CTI experiments is relatively limited, and compared with other segmentation models, U-Net has advantages such as a smaller number of parameters and faster training convergence, making it suitable for few-shot learning. In addition, U-Net has a fast inference speed, which can meet the demand for high-speed data processing in CTI experiments.As shown in Figure 4, this is the complete network architecture designed and used in this paper.

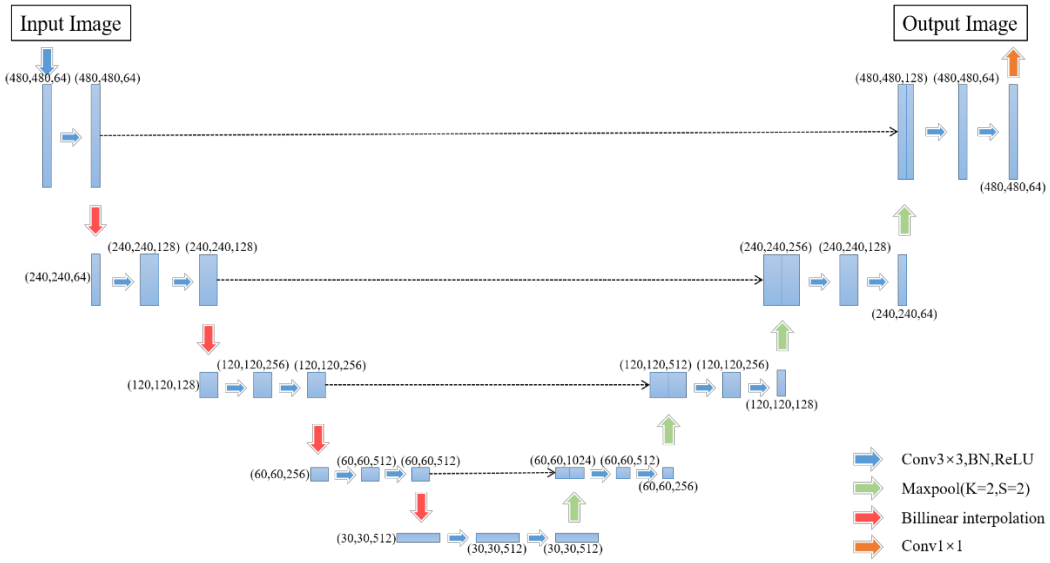

FIG. 4. U-Net network structure.

The trained neural network model was used to detect the CCD images of compact torus core fuel injection in the test set, and the results are shown in Figure 5: In the CCD images, the positions of the cold radiation rings marked by the red curve on the low-field side and the green curve on the high-field side respectively were accurately identified.

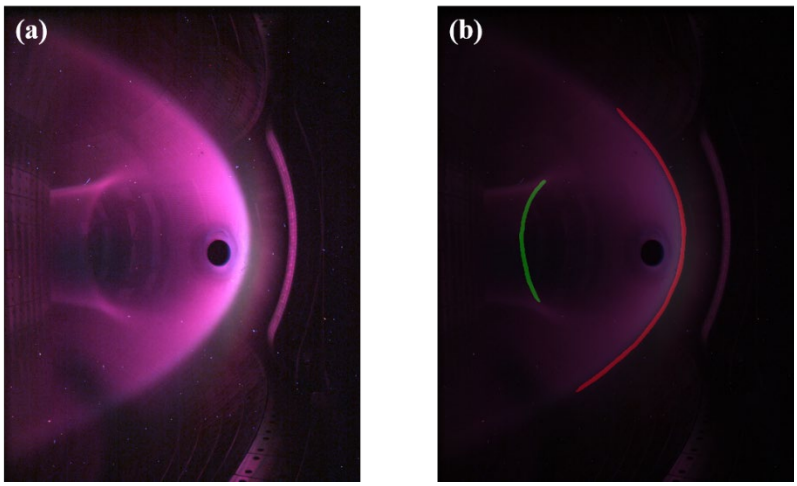

FIG. 5. Visible camera image of the CTI core fueling. (a)The red clippings are the raised edges, i.e., the cold radiating rings. (b)U-Nnet test results.

3. RESULTS

Using the dataset created through manual annotation, the optimally trained U-Net neural network model was applied to detect the test set, enabling the extraction of the position coordinates of the cold radiation ring in the images. Through camera calibration, the 2D coordinates in the images were converted to 3D coordinates in the real world, yielding the temporal variation of the injection depth during the compact torus core fuel injection process. As shown in Figure 6, cold radiation ring detection was performed on the visible light camera images of the #138609 shot fuel injection process in the validation set, and the corresponding variation of the injection depth was obtained. The depth variation during the core fuel injection process of the #138609 shot in the compact torus injection system is presented in Figure 6: the cold radiation ring appeared at 3.59 s, persisted for 0.08 s until 3.67 s, and its overall trend was consistent with the "first contraction then expansion" trend observed in the images.

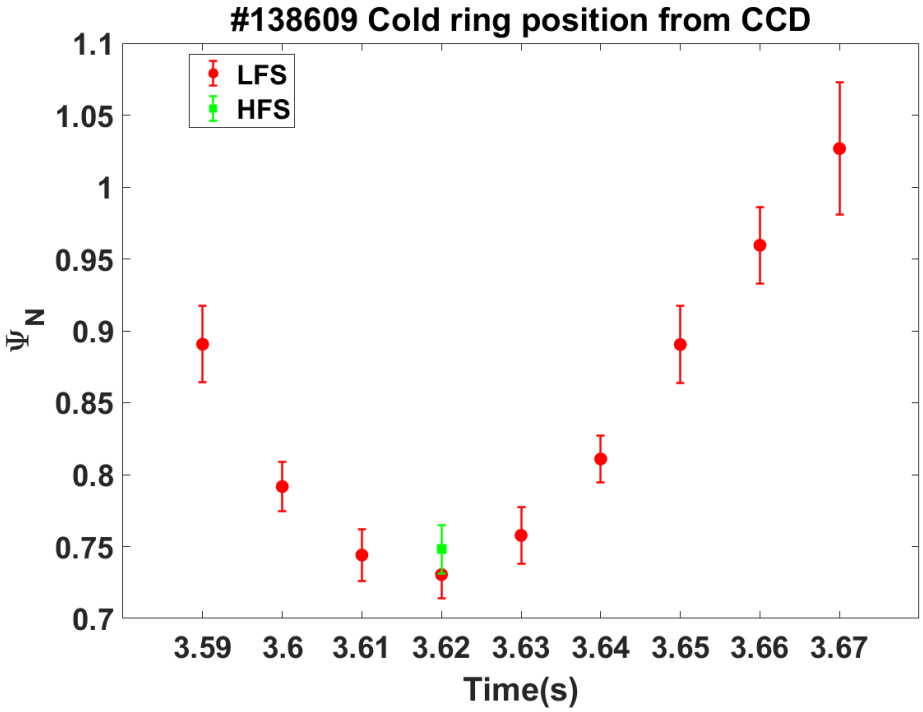

FIG. 6. Visible camera image of the CTI core fueling. (a)The red clippings are the raised edges, i.e., the cold radiating rings. (b)U-Nnet test results.

The position coordinates of the cold radiation ring obtained from the CCD images were projected onto the reflectometer density profile and marked with a red box, as shown in Figure 7. Experimental verification indicates that this dynamic evolution trend is highly consistent with the diagnostic results of the reflectometer (REFL), which further confirms the feasibility and correctness of the method proposed in this study.

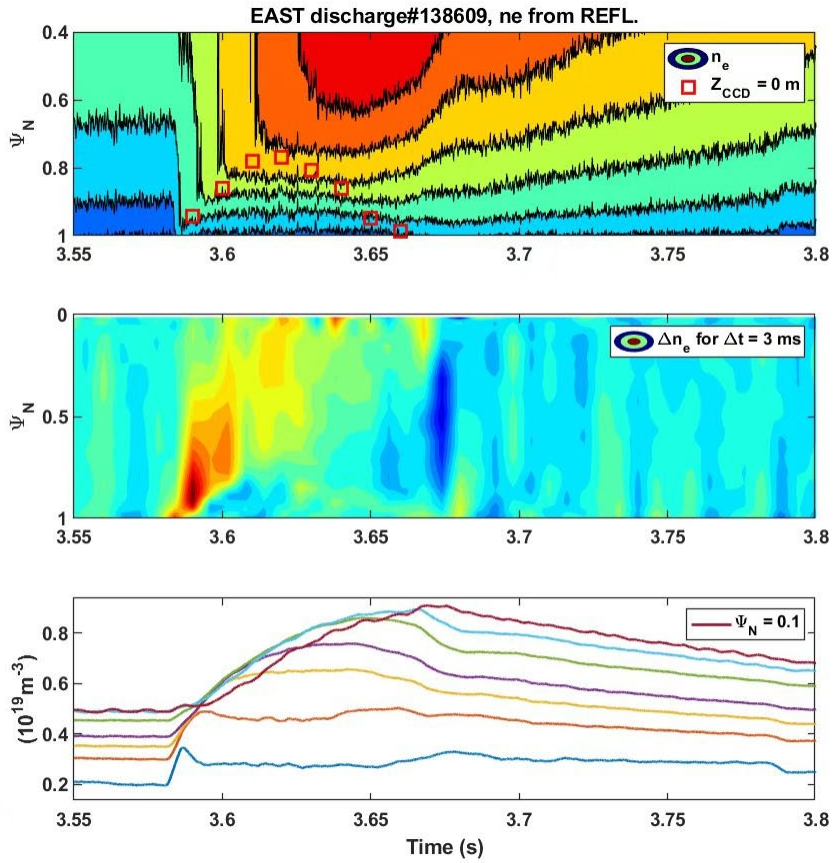

FIG. 7. Comparison of changes in injection depth.

4. CONCLUSION AND DISCUSSION

This study proposes a novel method for determining the injection depth of compact torus core fuel injection. A deep learning model was successfully applied to visible light camera images of the compact torus core fuel injection process to detect changes in the injection depth during the fuel injection. This addresses the issue of high latency in traditional diagnostic methods, which prevents them from meeting the demand for rapid feedback, and holds significant importance for research on the determination of core fuel injection depth. Finally, the detection results of the improved model were compared with the density diagnostic results from electron cyclotron emission (ECE) and reflectometers (REFL). The results show consistency, further verifying the feasibility and accuracy of the proposed method.

The method proposed in this paper can well identify the injection depth during the core fuel injection process of the compact torus injection system, and the proposal of this method is of great significance for determining the fuel injection depth. However, due to the very limited window period for fuel injection experiments on EAST, the sample size of experimental data is significantly restricted. In the future, the efficiency and accuracy of the algorithm's identification can be further improved by expanding the dataset.

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